TECHNICAL MEMORANDUM

SUBJECT: Development of Oyster Larval Transport Analysis (ADCIRC)

DATE: August 31, 2015

TO: Mary Baker, NOAA

FROM: Jessica Murray and Henry Roman, IEc, Joannes Westerink, University of Notre Dame

INTRODUCTION

The Deepwater Horizon (DWH) oil spill and its resultant response activities led to mortality impacts to oysters in the nearshore and subtidal zones that affected oysters of all sizes – spat (<25 millimeters (mm)), seed (between 25 and 75 mm), and market (>75 mm) (Grabowski, et al., 2015, Powers et al., 2015, Roman, 2015). Furthermore, these oyster losses contributed to ongoing reproductive failure documented by the Trustees' natural resource damage assessment (NRDA) sampling since 2010 (Grabowski et al., 2015). Studies have shown that oyster larvae can travel significant distances before settling (Kim et al., 2010). Understanding the source/sink relationships among regions is important for understanding the observed pattern of recruitment failure. In addition, nearshore oysters are important for local retention and seeding (Roman, 2015); thus, the relationship of larvae produced in the nearshore to the regional larval pool is key in understanding the reproductive failure. This technical memorandum describes the process by which we modeled and quantified the patterns of larval transport among regions and habitat types across the northern Gulf of Mexico. The following calculations support work by Westerink and colleagues (*in prep*) characterizing the mechanisms of failed oyster population recovery in this same area.

METHODOLOGY AND RESULTS

Advanced Circulation (ADCIRC) hydrodynamic model

In the Advanced Circulation (ADCIRC) model of larval transport, the trajectory of an oyster larvae is calculated by integrating

$$\frac{d\mathbf{x}(t;\mathbf{x}^0)}{dt} = \mathbf{u}(\mathbf{x}(t;\mathbf{x}^0),t)$$

(Equation 1)

where $x(t; x^0)$ is the position of the particle at time t, given the initial location of the particle x^0 at $t = 0$, and u is the velocity of the particle. Larvae are considered to be passive tracers fully submerged in the water and driven by the current. In this study, the current **u** is obtained from 2010 and 2011 hindcasts of the Gulf of Mexico using the high-resolution ADCIRC model (Luettich et al., 1992).

ADCIRC is a highly-parallelizable, unstructured finite element model that solves the Shallow Water Equations, which describe the conservation of mass and momentum under the incompressibility, Boussinesq and hydrostatic pressure assumptions. ADCIRC is capable of describing multi-scale features, from basin-wide phenomena to intricate, small-scale nearshore flows, such as inlets and flows around jetties. In this study, ADCIRC employs the "SL16" mesh which resolves the western Atlantic, the Gulf of Mexico, and with increasing resolution, the continental shelf, estuaries and wetlands that have mesh sizes as fine as 20-30 meters (m) in nearshore regions. Details of this mesh, bathymetry, and bottom friction can be found in Dietrich et al. (2010). The primary forcings of circulation in the hindcasts are wind, tides, atmospheric pressure, the Coriolis force, and varying rivers. The effect of wind-waves was not included in this study.

In the SL16 model, river inflow conditions were prescribed for the Mississippi River near Baton Rouge, LA and for the Atchafalaya River near Simmersport, LA based on the U.S. Army Corps of Engineers daily discharge data of the Mississippi River at Tarbert Landing, MS (US ACE, 2011). Note that Tarbert Landing is located downstream of the Old River Control Structure, which splits the volume of water in such a way that 30 percent of water volume flows into the Atchafalaya River (LUCEC, *n.d.*). The locations of both river forcing boundaries are downstream of the Old River Control Structure. Therefore, we used the discharge values of 3/7 of the flow at Tarbert Landing in specifying the inflows for the Atchafalaya River.

Using data from the TOPEX global tidal model, tides were forced on the Atlantic open-ocean boundary (along the 60°W longitude) with eight dominant astronomical tidal constituents: K_1, O_1, M_2, S_2, N_2, K_2, Q_1, and P_1 (Egbert et al., 1994). Tidal potential functions for these constituents were also forced within the domain. Note that, due to the resonant characteristic of the Gulf of Mexico and the Caribbean Sea, a period of model spin up and simulation were required in order for the initial transients to dissipate and dynamically correct tides to be generated. In this study, the period of the tidal spin-up was thirty days.

The effect of wind on water movement is represented in the model through surface stresses. Here, the wind surface stresses were determined by a quadratic air-sea drag law, which was based on the 10m wind velocities. In this study, we used the 10m North American Mesoscale Forecast System (NAM) wind products provided by the National Center for Environmental Prediction (NOAA, 2014). The spatial resolution of this wind product was approximately 12 kilometers and the temporal resolution was 6 hours. Note that the wind fields at the time in between two wind snapshots were obtained using linear interpolation. Depth-averaged currents from ADCIRC were recorded in 30 minute intervals (although the ADCIRC time step was significantly smaller), which were then used in tracking oyster larvae. Integration of the Lagrangian transport equation, Equation (1), was performed numerically using a 4th order Runge-Kutta time stepping scheme with an adaptive time step size to control the integration error. More precisely, the time step was chosen based on the error determined by comparing the position of the particle at time $t + \delta t$ when integrating with a time step size of δt and $\delta t/2$. If the error was greater than the given tolerance, the time step was cut in half and re-integrated until the error was less than the tolerance. Note, that with sufficiently small error tolerance in the time integration, the resulting time step size will also ensure that the particle will cross only one element at the end of each time marching step. The time marching procedure requires values of the velocity at the particle location. This value was obtained from the linear interpolation in time and space of the nodal data given on the finite element mesh. The particle was not allowed to cross a levee or a land boundary. If a new position of the particle crossed such boundaries, the particle position was instead set to a location on the boundary and subsequently determined by tracking along the edges.

To accurately describe currents for Lagrangian tracking it is important for a hydrodynamic model to properly resolve the complex coastal environment and include advection, tidal, wind and river forcings.

Oyster Larval Transport

We evaluated the spatial and temporal variability in the transport of oyster larvae throughout the northern Gulf of Mexico. The study area, consisting of source and sink polygons, extended from the Texas/Louisiana border (-94.9° W longitude) to the Alabama-Florida border (-87.4° W longitude) and from the shoreline to the shelf break (120-150 miles from shore). The temporal period was specified to capture oysters' main spawning period in this region, which was identified as the time from when the water temperature reached 25°C and lasted until the water temperature dropped below 25°C (Kim et al., 2010). In this case, the temporal period ranged from approximately April 28 to November 30 in both 2010 and 2011. Results were compiled for two time periods each year: Spring (April-June modeling) and Annual (April-November modeling). Oyster larvae release locations and timing in this model were intended to represent areas affected by shoreline oiling and cleanup actions, as well as areas and timing of river water releases and oiling in surface waters.

The modeling approach involved seeding the spatial domain repeatedly with approximately 10 million numerical drifters (i.e., oyster larvae) based on spatial habitat polygons, and then running the 2-dimensional[1] hydrodynamic particle tracking model forward in time to develop a temporally-dependent connectance matrix using the individual drifter tracks. The resulting connectivity matrices quantified the probability that a particle (larva) in a given cell (discretized spatial cell) translates to any other cell, including coastline locations.

During the modeling period of each year, we completed 27 model runs or larval "releases". The start time of each release coincided with every spring and neap tidal cycle, mid-stage between slack and ebb tide. Particles were tracked for 21 days from the time of release.

Two types of seeded habitat polygons were used: nearshore and subtidal. Each type was seeded using the same oyster density, for a total of approximately 3 million larvae in nearshore habitat and 7 million larvae in subtidal habitat. Nearshore habitat locations were identified as the area within a 100m buffer of saline vegetated marsh shoreline (50m buffer placed on both sides of contour for 100m total buffer width) within the study area. The buffer width was based on a 25 centimeter (cm) elevation shoreline contour. On the land-side of the contour, the buffer was clipped to a 50cm elevation, which was assumed to reasonably capture areas inundated by high tides. Subtidal habitat polygons represent areas included in oyster resource mapping work performed under NRDA work plans and the Louisiana Department of Wildlife and Fisheries (LDWF), for which oyster habitat percent cover estimates are available (BIO-WEST, 2010ab and 2011; NOAA, 2011, 2012, and 2013abc).

These nearshore and subtidal habitat polygons were divided by the subbasin boundaries shown in Figure 1, and connectivity matrix results were aggregated to these subbasins. The boundaries of most subbasins were based on Louisiana Coastal Study Areas (CSAs) (ERMA, 2015). Several of these CSAs, such as the areas in Terrebonne Bay and Barataria Bay, were further divided based on professional judgment, in order to elucidate larval transport within the bays, not just among them. The distribution of nearshore and subtidal habitats throughout the study area is shown in Figures 2 and 3.

Regional Larval Settlement

As a post-processing step once modeling for each 21-day release was completed, the average settlement probability of larvae in each subbasin was calculated in order to characterize larval transport within and among subbasins and habitat types. "Settlement" was defined as a particle (larva) spatially intersecting a habitat polygon at any point between 13 and 21 days post-release. This timing was based on the approximate maturation time of a larva. We assumed that the spatial intersection of a larva with a habitat polygon after this time represents the real life scenario of a negatively buoyant larva intersecting oyster reef and successfully settling. Once a larva "settled", its final location was recorded (by subbasin). Each modeled larva may settle only once; some larvae may not settle at all depending on their trajectory through the study area over time. This settlement analysis does not account for predation, genetic fitness, survival, or other factors that may promote or interfere with settlement.

Oyster reef in the study area was not continuous; patchy reefs and hummocks existed in sampled subtidal and nearshore areas (Powers et al., 2015, Roman, 2015). We created weighted settlement results for each subbasin by multiplying the raw quantity of larvae that settle in nearshore or subtidal habitat by the estimated percent of oyster habitat cover in that habitat type of the subbasin (Roman and Stahl, 2015).

[1] In shallow waters of the northern Gulf of Mexico, we assumed vertical mixing results in fairly uniform conditions throughout the water column; therefore, we assumed a 2D model reasonably captures the hydrodynamic forcing experienced by passive modeled larvae.

We calculated settlement averages for all larvae (nearshore and subtidal), and nearshore larvae only, for each of the time periods (Spring (April-June modeling) and Annual (April-November modeling)). For all larvae, we determined the average proportion of larvae settling in a given subbasin that originated from each other subbasin (i.e., the average composition of larvae settling in a subbasin based on their initial subbasin locations). This allowed us to summarize larval transport patterns throughout the modeled area and identify regions that exchange a greater or lesser proportion of larvae. Tables 1 through 4 display the results of the regional larval settlement analysis and demonstrate larval circulation within and, to some extent, among subbasins.

Nearshore Larval Settlement Analysis

For larvae that were released from nearshore habitat, we characterized the proportion of larvae that settled in nearshore versus subtidal habitat to inform our understanding of the contribution this population makes to the (potentially harvested) subtidal region. We calculated the average proportion of larvae originating in the nearshore of each subbasin that settled in each nearshore and subtidal habitats, regardless of final subbasin location. Table 5 displays the results of the nearshore larval settlement analysis, rounded to nearest 10%. Circulation modeling demonstrates that nearshore oysters and subtidal oysters form a common regional larval pool.

Table 1: Average larval settlement distribution by region (combines nearshore and subtidal larval transport) across Annual 2010 model releases, excluding values < 0.5%. Percentages represent the average percent of settling larvae modeled to recruit to habitat identified in row header from habitat in column header. TB = Terrebonne Bay; BB = Barataria Bay; MS W = Mississippi West; MS E = Mississippi East.

SETTLEMENT LOCATION	ORIGIN LOCATION																
	CSA6 NW	CSA6 SW	CSA6 NE	CSA6 SE	TB NW	TB SW	TB NE	TB SE	BB SW	BB NW	BB NE	BB SE	CSA 1S	CSA 1N	MS W	MS E	AL
CSA6 NW	75%	2%	22%	--	--	--	--	--	--	--	--	--	--	--	--	--	--
CSA6 SW	54%	19%	26%	1%	--	--	--	--	--	--	--	--	--	--	--	--	--
CSA6 NE	10%	--	57%	--	7%	11%	--	3%	--	--	--	--	--	--	--	--	--
CSA6 SE	9%	2%	40%	1%	9%	12%	--	9%	--	--	--	--	--	--	--	--	--
TB NW	--	--	--	--	75%	22%	--	3%	--	--	--	--	--	--	--	--	--
TB SW	--	--	--	--	4%	54%	--	41%	--	--	--	--	--	--	--	--	--
TB NE	--	--	--	--	--	--	81%	18%	--	--	--	--	--	--	--	--	--
TB SE	--	--	--	--	--	3%	5%	90%	1%	--	--	1%	--	--	--	--	--
BB SW	--	--	--	--	--	--	--	1%	62%	8%	3%	25%	--	--	--	--	--
BB NW	--	--	--	--	--	--	--	--	18%	79%	1%	2%	--	--	--	--	--
BB NE	--	--	--	--	--	--	--	--	3%	19%	63%	15%	--	--	--	--	--
BB SE	--	--	--	--	--	--	--	--	1%	2%	8%	90%	--	--	--	--	--
CSA 1S	--	--	--	--	--	--	--	--	--	--	--	--	95%	5%	--	--	--
CSA 1N	--	--	--	--	--	--	--	--	--	--	--	--	2%	94%	4%	--	--
MS W	--	--	--	--	--	--	--	--	--	--	--	--	--	20%	68%	12%	--
MS E	--	--	--	--	--	--	--	--	--	--	--	--	--	--	8%	78%	14%
AL	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	3%	97%

Table 2: Average larval settlement distribution by region (combines nearshore and subtidal larval transport) across Annual 2011 model releases, excluding values < 0.5%. Percentages represent the average percent of settling larvae modeled to recruit to habitat identified in row header from habitat in column header. TB = Terrebonne Bay; BB = Barataria Bay; MS W = Mississippi West; MS E = Mississippi East.

SETTLEMENT LOCATION	ORIGIN LOCATION																
	CSA6 NW	CSA6 SW	CSA6 NE	CSA6 SE	TB NW	TB SW	TB NE	TB SE	BB SW	BB NW	BB NE	BB SE	CSA 1S	CSA 1N	MS W	MS E	AL
CSA6 NW	80%	4%	15%	--	--	--	--	--	--	--	--	--	--	--	--	--	--
CSA6 SW	51%	31%	17%	2%	--	--	--	--	--	--	--	--	--	--	--	--	--
CSA6 NE	20%	--	54%	--	4%	--	--	--	--	--	--	--	--	--	--	--	--
CSA6 SE	16%	12%	37%	2%	7%	--	--	--	--	--	--	--	--	--	--	--	--
TB NW	--	--	--	--	88%	11%	--	1%	--	--	--	--	--	--	--	--	--
TB SW	--	--	--	--	8%	58%	--	34%	--	--	--	--	--	--	--	--	--
TB NE	--	--	--	--	--	--	81%	19%	--	--	--	--	--	--	--	--	--
TB SE	--	--	--	--	--	4%	5%	90%	1%	--	--	--	--	--	--	--	--
BB SW	--	--	--	--	--	--	--	2%	60%	13%	3%	21%	--	--	--	--	--
BB NW	--	--	--	--	--	--	--	--	10%	88%	1%	1%	--	--	--	--	--
BB NE	--	--	--	--	--	--	--	--	2%	14%	70%	13%	--	--	--	--	--
BB SE	--	--	--	--	--	--	--	--	1%	1%	9%	89%	--	--	--	--	--
CSA 1S	--	--	--	--	--	--	--	--	--	--	--	--	93%	7%	--	--	--
CSA 1N	--	--	--	--	--	--	--	--	--	--	--	--	4%	93%	3%	--	--
MS W	--	--	--	--	--	--	--	--	--	--	--	--	--	23%	69%	8%	--
MS E	--	--	--	--	--	--	--	--	--	--	--	--	--	2%	18%	72%	9%
AL	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	7%	93%

Table 3: Average larval settlement distribution by region (combines nearshore and subtidal larval transport) across Spring 2010 model releases, excluding values < 0.5%. Percentages represent the average percent of settling larvae modeled to recruit to habitat identified in row header from habitat in column header. TB = Terrebonne Bay; BB = Barataria Bay; MS W = Mississippi West; MS E = Mississippi East.

SETTLEMENT LOCATION	ORIGIN LOCATION																
	CSA6 NW	CSA6 SW	CSA6 NE	CSA6 SE	TB NW	TB SW	TB NE	TB SE	BB SW	BB NW	BB NE	BB SE	CSA 1S	CSA 1N	MS W	MS E	AL
CSA6 NW	72%	1%	27%	--	--	--	--	--	--	--	--	--	--	--	--	--	--
CSA6 SW	54%	15%	34%	2%	--	--	--	--	--	--	--	--	--	--	--	--	--
CSA6 NE	10%	--	55%	--	12%	2%	--	--	--	--	--	--	--	--	--	--	--
CSA6 SE	9%	--	45%	--	10%	4%	--	--	--	--	--	--	--	--	--	--	--
TB NW	--	--	--	--	75%	24%	--	--	--	--	--	--	--	--	--	--	--
TB SW	--	--	--	--	7%	68%	--	25%	--	--	--	--	--	--	--	--	--
TB NE	--	--	--	--	--	1%	78%	21%	--	--	--	--	--	--	--	--	--
TB SE	--	--	--	--	--	7%	5%	86%	1%	--	--	--	--	--	--	--	--
BB SW	--	--	--	--	--	--	--	5%	60%	9%	5%	21%	--	--	--	--	--
BB NW	--	--	--	--	--	--	--	--	21%	76%	1%	1%	--	--	--	--	--
BB NE	--	--	--	--	--	--	--	--	1%	18%	61%	20%	--	--	--	--	--
BB SE	--	--	--	--	--	--	--	--	--	1%	7%	92%	--	--	--	--	--
CSA 1S	--	--	--	--	--	--	--	--	--	--	--	--	97%	3%	--	--	--
CSA 1N	--	--	--	--	--	--	--	--	--	--	--	--	5%	92%	3%	--	--
MS W	--	--	--	--	--	--	--	--	--	--	--	--	--	18%	68%	14%	--
MS E	--	--	--	--	--	--	--	--	--	--	--	--	--	--	7%	81%	11%
AL	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	2%	98%

Table 4: Average larval settlement distribution by region (combines nearshore and subtidal larval transport) across Spring 2011 model releases, excluding values < 0.5%. Percentages represent the average percent of settling larvae modeled to recruit to habitat identified in row header from habitat in column header. TB = Terrebonne Bay; BB = Barataria Bay; MS W = Mississippi West; MS E = Mississippi East.

SETTLEMENT LOCATION	ORIGIN LOCATION																
	CSA6 NW	CSA6 SW	CSA6 NE	CSA6 SE	TB NW	TB SW	TB NE	TB SE	BB SW	BB NW	BB NE	BB SE	CSA 1S	CSA 1N	MS W	MS E	AL
CSA6 NW	75%	2%	22%	1%	--	--	--	--	--	--	--	--	--	--	--	--	--
CSA6 SW	63%	9%	27%	1%	--	--	--	--	--	--	--	--	--	--	--	--	--
CSA6 NE	13%	--	15%	--	--	--	--	--	--	--	--	--	--	--	--	--	--
CSA6 SE	4%	--	24%	--	--	--	--	--	--	--	--	--	--	--	--	--	--
TB NW	--	--	--	--	92%	7%	--	1%	--	--	--	--	--	--	--	--	--
TB SW	--	--	--	--	8%	48%	--	44%	--	--	--	--	--	--	--	--	--
TB NE	--	--	--	--	--	--	77%	23%	--	--	--	--	--	--	--	--	--
TB SE	--	--	--	--	--	3%	5%	90%	1%	--	--	1%	--	--	--	--	--
BB SW	--	--	--	--	--	--	--	6%	56%	16%	4%	17%	--	--	--	--	--
BB NW	--	--	--	--	--	--	--	--	11%	89%	--	--	--	--	--	--	--
BB NE	--	--	--	--	--	--	--	--	--	6%	75%	19%	--	--	--	--	--
BB SE	--	--	--	--	--	--	--	--	--	1%	9%	89%	--	--	--	--	--
CSA 1S	--	--	--	--	--	--	--	--	--	--	--	--	94%	6%	--	--	--
CSA 1N	--	--	--	--	--	--	--	--	--	--	--	--	9%	90%	--	--	--
MS W	--	--	--	--	--	--	--	--	--	--	--	--	1%	33%	57%	9%	--
MS E	--	--	--	--	--	--	--	--	--	--	--	--	--	5%	26%	65%	3%
AL	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	7%	92%

Table 5: Average nearshore larval settlement distribution by region for each season (Annual or Spring) and year (2010 and 2011), rounded to the nearest 10%. Row labels represent the origin region of nearshore larvae. *% Settle in Nearshore* represents the average percent of settling nearshore larvae modeled to recruit to nearshore habitat. *% Settle in Subtidal* represents the average percent of settling nearshore larvae modeled to recruit to subtidal habitat. TB = Terrebonne Bay; BB = Barataria Bay; MS W = Mississippi West; MS E = Mississippi East.

NEARSHORE ORIGIN LOCATION	**Annual 2010**		**Annual 2011**		**Spring 2010**		**Spring 2011**	
	% Settle in Nearshore	*% Settle in Subtidal*	*% Settle in Nearshore*	*% Settle in Subtidal*	*% Settle in Nearshore*	*% Settle in Subtidal*	*% Settle in Nearshore*	*% Settle in Subtidal*
TB NW	20%	80%	30%	70%	20%	80%	30%	70%
TB SW	30%	70%	20%	80%	40%	60%	20%	80%
TB NE	50%	50%	50%	50%	50%	50%	50%	50%
TB SE	40%	60%	40%	60%	40%	60%	40%	60%
BB SW	50%	50%	50%	50%	50%	50%	50%	50%
BB NW	30%	70%	30%	70%	30%	70%	30%	70%
BB NE	60%	40%	50%	50%	50%	50%	40%	60%
BB SE	10%	90%	10%	90%	10%	90%	10%	90%
CSA 1S	10%	90%	10%	90%	10%	90%	10%	90%
CSA 1N	20%	80%	20%	80%	10%	90%	10%	90%
MS W	20%	80%	20%	80%	20%	80%	30%	70%
MS E	40%	60%	40%	60%	40%	60%	40%	60%
AL	10%	90%	10%	90%	10%	90%	10%	90%

Figure 1: Subbasin boundaries used in larval settlement analysis.

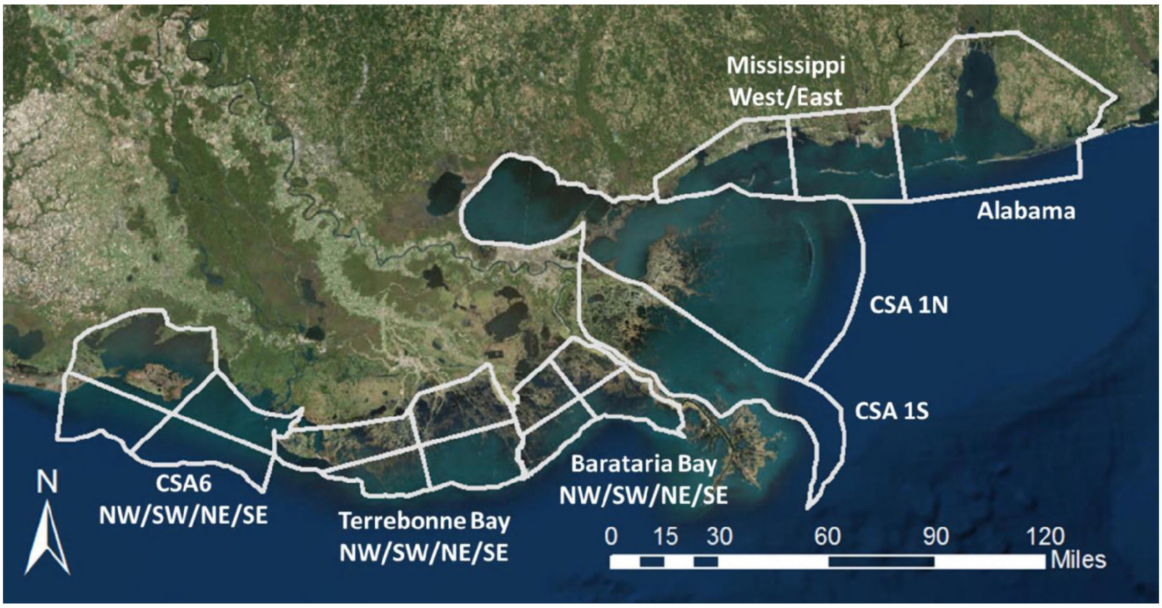


Figure 2: Nearshore and subtidal habitat seeding areas of CSA 6, Terrebonne Bay and Barataria Bay used in ADCIRC larval transport modeling. Subbasin boundaries outlined in white. Only larvae originating from and settling within subbasin boundaries were included in the settlement analyses, i.e., nearshore settlement and larval release areas in the Mississippi River Bird's Foot Delta outside of the Barataria Bay and CSA 1S subbasin boundaries were excluded from the analyses.

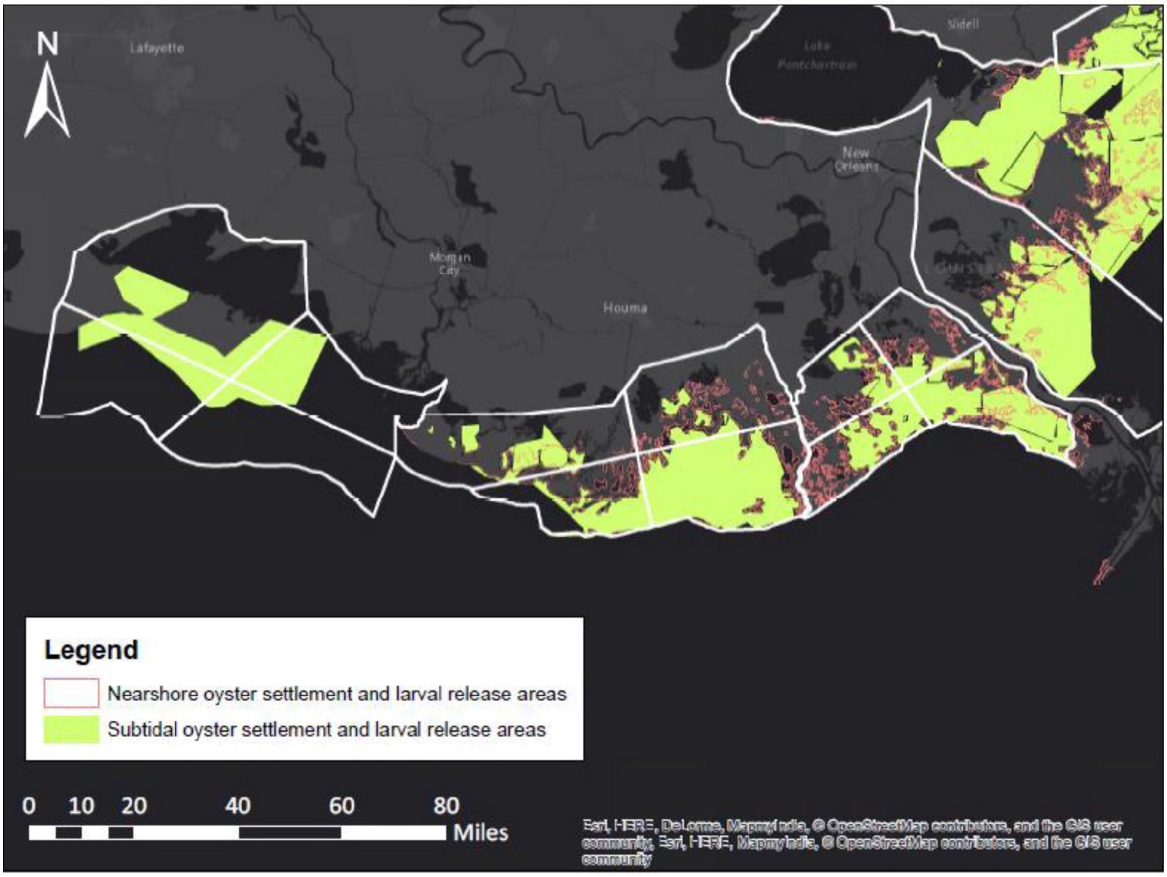
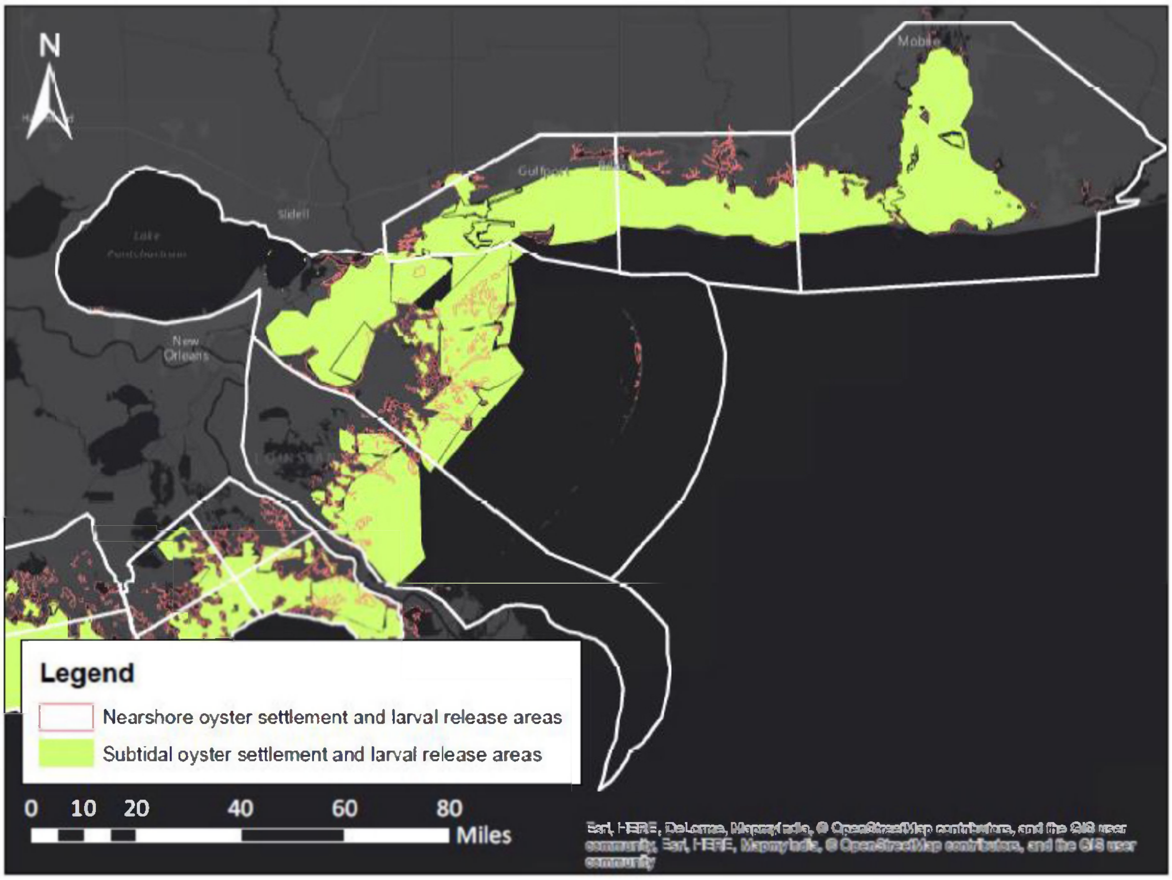


Figure 3: Nearshore and subtidal habitat seeding areas of CSA 1S, CSA 1N, Mississippi West, Mississippi East and Alabama used in ADCIRC larval transport modeling. Subbasin boundaries outlined in white. Only larvae originating from and settling within subbasin boundaries were included in the settlement analyses, i.e., nearshore and subtidal settlement and larval release areas in Mississippi Sound north of the Mississippi West and East subbasin boundaries were excluded from the analyses.



DWH-AR0270412

REFERENCES

BIO-WEST, Inc. 2010a. Water Bottom Assessment (Survey) in Mississippi Sound. Internal Technical report of Louisiana Department of Wildlife and Fisheries.

BIO-WEST, Inc. 2010b. Water Bottom Assessment (Survey) in Black Bay. Internal Technical report of Louisiana Department of Wildlife and Fisheries.

BIO-WEST, Inc. 2011. Water Bottom Assessment (Survey) in Breton Sound. Internal Technical report of Louisiana Department of Wildlife and Fisheries.

Dietrich, J. C., S. Bunya, J. J. Westerink, B. A. Ebersole, J. M. Smith, J. H. Atkinson, R. Jensen, D. T. Resio, R. A. Luettich, C. Dawson, V. J. Cardone, A. T. Cox, M. D. Powell, H. J. Westerink, and H. J. Roberts. 2010. A high-resolution coupled riverine flow, tide, wind, wind wave, and storm surge model for Southern Louisiana and Mississippi. Part II: Synoptic description and analysis of hurricanes Katrina and Rita. Monthly Weather Review 138:378-404.

Egbert, G. D., A.F. Bennett, and M.G.G. Foreman. 1994. TOPEX/POSEIDON tides estimated using a global inverse model. Journal of Geophysical Research: Oceans 99(C12):24821-24852.

Environmental Response Management Application (ERMA). 2015. Deepwater Gulf Response. National Oceanic and Atmospheric Administration. Available: http://response.restoration.noaa.gov/maps-and-spatial-data/environmental-response-management-application-erma/erma-gulf-response.html, accessed 09/08/2015..

Grabowski, J. H., H. Marrison, J. Murray, S. P. Powers, H. Roman, and S. Rouhani. 2015. Oyster Recruitment Failure in the Northern Gulf of Mexico as a Consequence of the 2010 Deepwater Horizon Oil Spill. DWH Shoreline NRDA Technical Working Group Report.

Kim, C.K., K. Park, S. P. Powers, W. M. Graham, and K. M. Bayha. 2010. Oyster larval transport in coastal Alabama: Dominance of physical processes over biological behavior in a shallow estuary. Journal of Geophysical Research-Oceans 115 (10): C10019

Loyola University's Center for Environmental Communication (LUCEC). *n.d.* Louisiana Old River control complex and Mississippi river flood protection. Available online from http://www.americaswetlandresources.com/background_facts/detaildstory/LouisianaRiverControl.html.edu.

Luettich, Jr. R. A., J. J. Westerink, and N. W. Scheffner. 1992. ADCIRC: An advanced three-dimensional circulation model for shelves, coasets, and estuaries: theory and methodology of ADCIRC-2DDI and ADCIRC-3DL. Technical report DRP-92-6, US Army Corps of Engineers (US ACE), DC.

National Oceanic and Atmospheric Administration (NOAA). 2011. Mississippi Canyon 252 Spill Oyster Transition Plan. DWH Oyster NRDA Technical Working Group Workplan.

National Oceanic and Atmospheric Administration (NOAA). 2012. Mississippi Canyon 252 Spill 2012 Oyster Quadrat Abundance Monitoring Plan. DWH Oyster NRDA Technical Working Group Workplan.

National Oceanic and Atmospheric Administration (NOAA). 2013a. Mississippi Canyon 252 Spill 2013 Oyster Quadrat Abundance Monitoring Plan. DWH Oyster NRDA Technical Working Group Workplan.

National Oceanic and Atmospheric Administration (NOAA). 2013b. Mississippi Canyon 252 Spill 2013 Nearshore Oyster Sampling Plan. DWH Oyster NRDA Technical Working Group Workplan.

National Oceanic and Atmospheric Administration (NOAA). 2013c. Mississippi Canyon 252 Spill Oyster Resource Mapping Plan. DWH Oyster NRDA Technical Working Group Workplan.

National Oceanic and Atmospheric Administration (NOAA). 2014. North American Mesoscale Forecast System (NAM) wind products. NOAA National Operational Model Archive & Distribution System. Available online from http://nomads.ncdc.noaa.gov/data/namanl/.

Powers, S. P., J. H. Grabowski, H. Roman, A. Geggel, S. Rouhani, J. Oehrig, M. Baker. 2015. Consequences of Large Scale Hydrographic Alteration During the Deepwater Horizon Oil Spill on Subtidal Oyster Populations. DWH Oyster NRDA Technical Working Group Report.

Roman, H. 2015. Technical Memorandum. Development of Oyster Nearshore Injury Quantification. DWH Oyster NRDA Technical Working Group Report.

Roman, H. and M. B. Stahl. 2015. Technical Memorandum. Estimation of Oyster Resource in the Northern Gulf of Mexico. DWH Oyster NRDA Technical Working Group Report.

US Army Corps of Engineers (US ACE). 2011. Mississippi River Basin Stage Data. Hydraulics Branch, CEMVN-ED-HD, Team New Orleans. Available online from http://www2.mvn.usace.army.mil/eng/edhd/wcontrol/miss.asp.

Westerink, J.J., Powers, S.P., Murray, J., Meixner, J., Wirasaet, D., Roman, H., Suhardjo, A., et al. *In prep*. Working title: Oyster Population Connectivity in the northern Gulf of Mexico and Mechanisms of Recovery Failure post-Deepwater Horizon Oil Spill. DWH Oyster NRDA Technical Working Group.